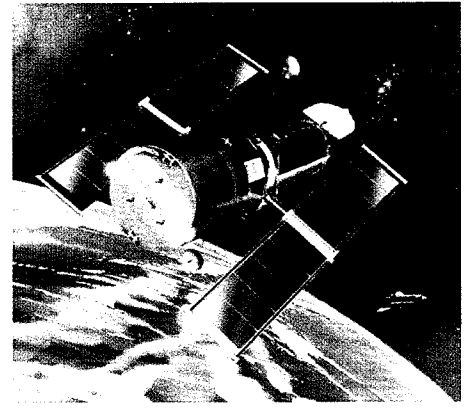
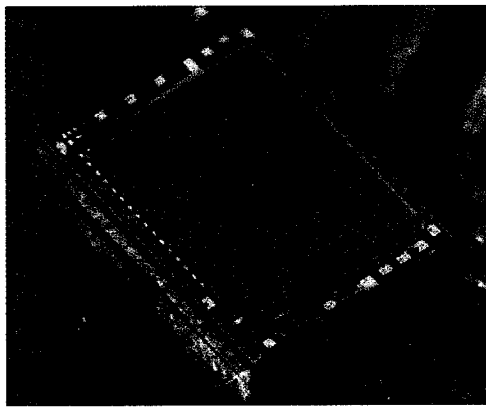
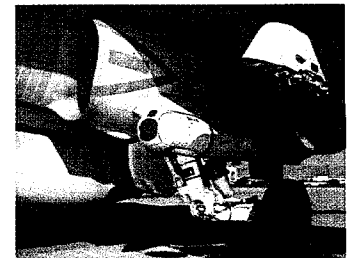
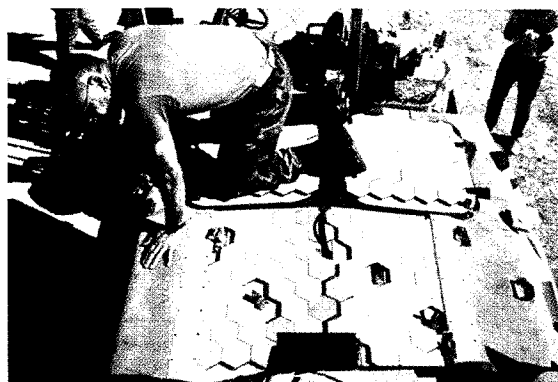
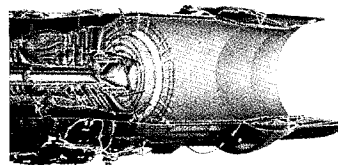
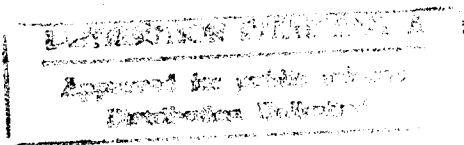
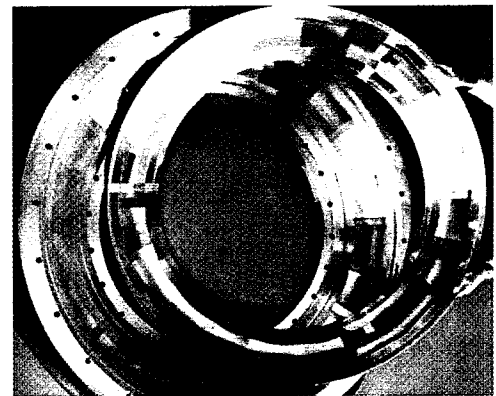
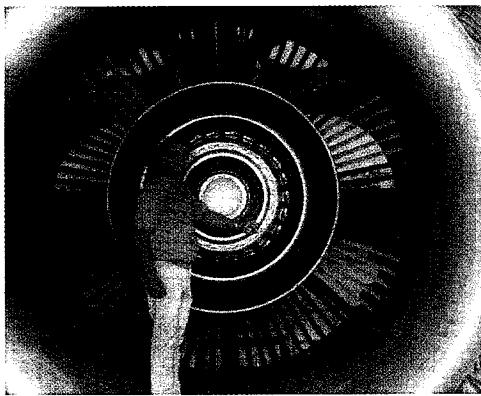


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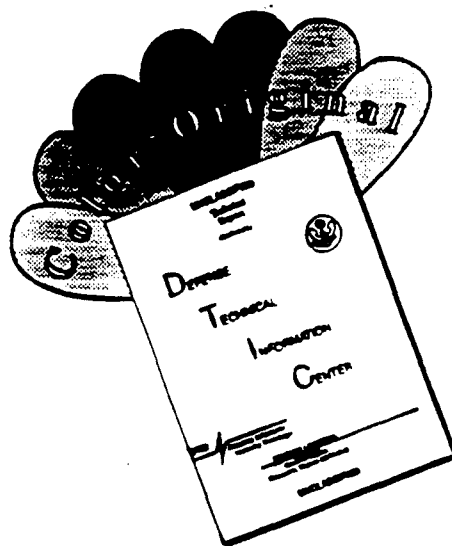
# USES OF DARPA MATERIALS SCIENCES TECHNOLOGY IN DoD SYSTEMS



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Principal Investigator  
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Attached is the final report on the above grant and is being distributed in accordance with the grant instructions on "Report and Other Deliverables Distribution".

**USES OF DARPA  
MATERIALS SCIENCES TECHNOLOGY  
IN  
DoD SYSTEMS**

by  
Dr. C. Martin Stickley  
Center for Research and Education in Optics and Lasers  
University of Central Florida  
Orlando, Florida

May 1996

Sponsored by:  
Dr. Ben Wilcox  
Defense Advanced Research Projects Agency  
Defense Sciences Office  
Materials Sciences Division  
Arlington, Virginia

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## EXECUTIVE SUMMARY

The purpose of this study was to document examples of ARPA-funded (or DARPA if the program began after 1975) research in materials sciences which resulted in technology or products being used in Department of Defense systems or other government agency's systems. An important exception in this report is the inclusion of the ARPA Interdisciplinary Labs Program which provided a materials-educated workforce in the defense community and which created the field of 'materials science and engineering'.

The process of developing the information included in this study was the laborious one of tracking down the technology user through a series of phone calls, usually starting with the person who was the ARPA Program Manager for the project in question. This study was carried out at a low level over a period of several years, and documents programs which produced a technology or a product which was used in a DoD or other agency's system. These programs, listed chronologically, and examples of their applications are:

Explosive Forming in the manufacture of afterburner rings for the SR-71, rocket engine seals, aircraft skin for the F3 Orion, jet engine diffusers, jet engine sound suppressors, APU heat shields, and others.

Beryllium Optics for ABMDA's Midcourse Airborne Target Signature Program, and the primary mirror assembly for JPL's IR Telescope Technology Testbed for eventual use in NASA's Space Infrared Telescopic Facility.

Rare Earth Magnets used in the VTR-51145N5 for the AN/ALQ-135 EW system on the F-15, the QKW-2048 for the Navy EHF Satcom Program, and in cryocoolers for IR sensors used in the Cobra helicopter and the F-18.

Ceramic Turbine: Brittle Materials Design led to ceramics being used in the 8V71-T engine which powers the M-998 ammunition carrier. More significantly the program led to the development and application of ceramics throughout the world as high tech, engineering materials.

Glassy Carbon as heart valve implants for veterans and others; small joints are to be produced starting in 1997.

High Performance IR Optics as FLIR windows for the F-111 Pave Tack System and the F/A-18, and as optics for commercial laser and EO systems.

Platinum Silicide Focal Plane Arrays in the AAQ-23 camera for the B-52 fleet.

Advancement of Reliability, Processing, and Automation of Integrated Circuits resulted in device reliability improvements in hybrid and IC technology used in the Trident submarine and other DoD systems, and made possible large military hybrid circuits which utilize more than 500 wire bonds each.

Gallium Arsenide Integrated Circuits are used in the Precise Lightweight GPS Receiver; pseudo-random code generator chips for NSA; accumulator and rate reducer chips for smart terminals, and other applications.

Rapid Solidification Rate Processing resulted in advanced superalloy materials used as compressor outer air seals in the 4th and 5th shrouds and 6th and 12th stators in the F100-PW-220 engine for the F-15 and F-16 aircraft.

Computer Aids for VLSI Modeling resulted in the SUPREM computer codes used to make radiation-hard ICs for Trident, and ICs for MILSTAR, NSA cryptoboxes, and many others. Codes transferred to over 300 sites for aids in silicon and gallium arsenide integrated circuit manufacturing.

Metal Matrix Composites for spaceborne antenna mast applications, including the antenna mast for the Hubble Space Telescope.

Lightweight Aluminum-Lithium Alloys for the Titan Payload Adapter and various sensitive space applications.

Precision, High Performance Ceramic Bearings in gyros for the F-18, AV-8, F-16, several helicopters, and in bearings for IR seekers for the Navy Missile Homing Improvement Program.

Retirement for Cause led to extended service use of turbine rotors of the AF F100-PW 100/200 engine with a projected saving of over \$1.2B in procurement, maintenance and fuel saving costs over the period of 1986-2005.

Silicon Carbide Particulate-Reinforced Aluminum for use as F-16 ventral fins and as the fan exit guide vanes for large turbofan engines such as the P&W 4090 used on the 777.

Ceramic Composite Armor for protection of flight crews in C-141s flying in Bosnia from small arms fire and for application to Light Armored Vehicles.

Insitu Metal Matrix Composites for the compressor inner shroud for the F-22 ATF and for the P&W F-119 engine.

High Temperature Superconductors for an ultrahigh Q, rf cavity for the oscillator in the SPQ-9 shipboard radar. The result will be a high spectral purity, low off-frequency phase noise, rf source which will enable the radar to have very high clutter rejection for detection of cruise missiles in clutter.

## INTRODUCTION

The purpose of this report is to document examples of ARPA-funded research and development in materials sciences which resulted in technology or products being used in Department of Defense systems or systems used by other government agencies.

The author of this report, Dr. C. Martin Stickley, was selected to carry out this study by Dr. Ben Wilcox of the Materials Sciences Division of the Defense Sciences Office. The author has had substantial interactions with the Materials Sciences Office/Division dating from 1968 to the present. He was the Director of the Materials Sciences Office from 1972 to 1976, and has known all of the Directors and many of the program managers and their programs over the past 25 years.

Program topics selected for funding were generally the idea of the ARPA program manager or the Office Director. ARPA sought experienced R&D scientists/managers to join the organization and develop programs to attack problems or pursue opportunities which were well known of by the program manager. Upon presentation of these to the Director of ARPA, the go-ahead would be given if the Director concurred. In the 60's and 70's in the Materials Sciences area, it almost never occurred that the Materials Sciences organization funded a program whose results were expected to be retrofitted into a DoD system. However, this started to change in the late 80's with the advent of technology insertion programs. The job of the Materials Sciences technical staff was to find those materials-based technology topics which, if successfully developed, would solve an important problem or create an important new capability for the DoD. In the 1990's, the dual use (military/civilian) nature of research became important with the Congressionally-mandated Technology Reinvestment Project which DARPA managed.

While the Materials Sciences technical staff developed ideas for programs without the use of consultants, ARPA/MSO did create the Materials Research Council, which was comprised of about 20 senior university professors who were experts in the various facets of materials science (physics, chemistry, metallurgy, ceramics, mechanical engineering, polymer science, electronics, optics, etc.). The MRC was formed in 1968 as a mechanism to help heal the wounds in DoD-university relationships as a result of the Vietnam War. It was expected that the MRC members would become knowledgeable of the DoD materials problems and take this knowledge back to their universities with the thought that, with the influence of these senior professors, research might be initiated on DoD materials problems. This did happen, and as time evolved the MRC became a sounding board and a "consulting" resource for the Materials Sciences technical staff. On occasion, ideas would originate from the MRC which would lead to an important ARPA program. A good example of this is "splat cooling" which was first studied by Paul Duwez of Cal Tech and a MRC member. This idea led to ARPA efforts on fine powder technology and eventually to the Rapid Solidification Rate Processing program which led to new materials for engine seals. This program is described in this report. The MRC members, by virtue of their reviews of Materials Sciences programs during their summer meetings, had a substantial impact on the quality of these programs. In 1990, the MRC was renamed the Defense Sciences Research Council.

The body of this report begins with a description of the most significant program in materials which ARPA funded: the ARPA Interdisciplinary Labs program. Following this, a brief description is given of nineteen ARPA Materials Sciences programs which led to products or technologies which were used in DoD systems or systems of other government agencies. Included is a description of the technology, the contractor, the application of the technology, its payoff, and why it "worked", that is, the principal management or technical factors for it eventually being used in a system. This insight was sought in each case so that DARPA and others might better learn from these past successes.

This report has appendices listing the major program areas funded by Materials Sciences between 1960 and the late 80's, and the names of the ARPA Materials Sciences program managers and office directors from 1960 until the present time.

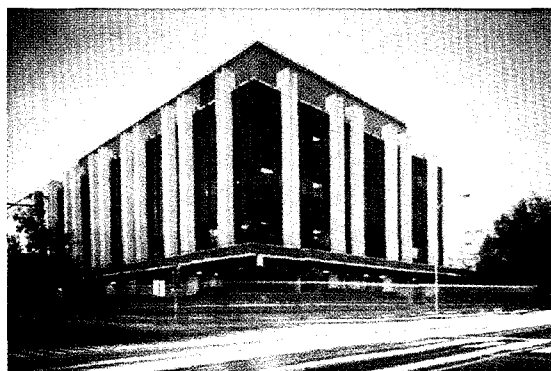


## **The ARPA Interdisciplinary Labs (IDLs): Creating the Field of Materials Science and Engineering**

**Objectives:** Increase the academic research capability in materials-related disciplines of science and engineering. Increase the output of highly trained specialists in materials-related fields.

**Contractors:** Cornell, Penn, Brown, Northwestern, Chicago, Harvard, MIT, Maryland, N. Carolina, Purdue, Stanford, Illinois

**Time Period:** 1960-1972



IDL Building at the University of Pennsylvania

### **Key Factors in Program Success:**

- Broad support at the highest levels of the nation
- Three year forward funding
- 10 year ARPA commitment to pay for buildings
- Managed at the universities
- Deep financial support - \$158M over 12 years.

### **Application and Impact:**

- The field of Materials Science and Engineering was created
- Ph.D. output rose 75% by 1972
- MS&E graduates became technology leaders and managers in U.S. industry, government and universities
- Many "interdisciplinary" research contributions

## **THE ARPA INTERDISCIPLINARY LABS (IDLS): CREATING THE FIELD OF MATERIALS SCIENCE AND ENGINEERING**

“The unprecedented progress of science and engineering in the second half of the twentieth century has advanced many worthy goals - beginning with the defense of freedom - and has fostered understanding of the world, its inhabitants, and the cosmos. In this context, materials research and development stands out - both as a twentieth century phenomenon and as an endeavor that bridges the often-disparate objectives of understanding nature and of ensuring freedom.”<sup>1</sup>

In 1960, ARPA initiated the federal government's bold experiment to create new institutions at major research universities for focusing the traditional scientific and technological disciplines - physics, chemistry, metallurgy, ceramics, electrical engineering, mechanical engineering - to develop the science of materials. Through the years following WWII, it had become the conviction of top-level scientific administrators - John von Neumann, then the Chairman of AEC's General Advisory Committee; Frederick Seitz and Harvey Brooks, then leaders of ONR's Solid State Sciences Advisory Board; James Killian, Science Advisor to President Eisenhower; William O. Baker, then of Bell Labs; and Herbert York, then Director, Defense Research and Engineering - that the design and creation of new materials, such as composites, high-temperature coatings, or heat shields, would require true collaboration among chemists, metallurgists, physicists, and engineers. Heightened action towards creating a National Materials Program, of which the ARPA Interdisciplinary Labs would become the principal part, was triggered by the Soviet Union's successful launch of Sputnik on October 4, 1957. In the spring of 1959, York agreed to DoD's taking the prime responsibility and, on June 8, 1959, assigned the program to ARPA, a young agency with little doctrine, a passion for innovation, and which held the conviction that the U.S. should never be second best in any technology of consequence.

The type of collaboration between academia and government implied by this far-reaching program required the universities to take the risks of expansion - commitment of centrally-located space for building construction, and expansion of tenure-track professional appointments - on the expectation that ARPA would follow through on its commitments it made at that time: initial three-year forward funding with a fourth year of funding added anew every fiscal year, and reimbursement over ten years for the new construction required to do modern experimentation in materials. Risks were also accepted on ARPA's side, especially that the practice of central management responsibility at the university for the allocation of the funds would be done in the combined interest of ARPA and the university.

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<sup>1</sup>Wm. O. Baker, former Chairman, Board of Directors, AT&T Bell Laboratories, in *Advancing Materials Research*, National Academy Press, 1987.

The impact on the universities involved was described by R. Sproull, who had the unique experience both of running an IDL laboratory and being an ARPA director:

“The important features at each university were the following. First, that an umbrella contract provided for continuity of support and for the ability to buy large quanta of equipment and facilities. Second, a local director committed a substantial fraction of his career to making the program succeed. He could use the longevity of support to extract concessions from the university and departmental administrators. Third, the contract provided, in most cases, reimbursement over 10 years for the new construction required to do modern experimentation on materials. Fourth, the longevity of the contract induced the university to allocate to the project scarce and prime space in the middle of the campus, thereby establishing the maximum informal connections among disciplines. Fifth, central experimental facilities (such as those for electron microscopy or crystal growth) could have state-of-the-art equipment, even if it was very expensive, and they served as a mixing ground for students and faculty from several disciplines. Sixth, an executive committee composed of people with power and influence in the individual disciplines but oriented toward the success of the program helped the director over the rough spots with department chairmen, people who often were overly protective of their bishoprics and palatinates. Seventh, a contract was not given to an institution unless it had a strong disciplinary base on which to build. Interdisciplinary programs perched on weak disciplines are dangerous; interdisciplinary work already had a bad name on many campuses because of programs alleged to be interdisciplinary but without disciplines (on many campuses home economics was the example cited). Eighth, individual grants and contracts with federal agencies continued; most well-established principal investigators received the majority of their support from some other agency and might enjoy help from the program only in the central facilities or the building space. Thus, when the executive committee and director found that they had to say “no” to a local high priest, it was not really “no” but only “no” with the umbrella contract’s money, and that made life easier.”

Funding provided by ARPA was about \$158 million over the course of the program from 1960 to 1972, at which point in time it was transferred to the NSF and renamed The Materials Research Laboratories (MRL’s). This NSF program exists today with seven of the original IDL’s as active MRL’s. During its funding peak (\$18.7 million) in 1969 the program involved a total of nearly 600 faculty members and 2385 graduate students; 360 doctoral degrees were awarded, and more than 2000 papers were published. Research accomplishments later identified by the staffs of DARPA and the NSF as examples of ones which would have been difficult or infeasible to achieve under traditional disciplinary project support include:

- organic conductors - leading to new, cheaper laser harmonic generators and new materials for batteries
- splat cooling - leading to the rapid solidification process for manufacture of higher temperature materials for jet engines (see the RSR process later in this report)

- ultra-low temperatures - leading to unexpected phase transitions and providing background for developments in superconductors
- phase transitions - leading to understanding of materials like polyvinyl fluoride which has good infrared sensitivity at room temperature
- fracture mechanics - formulation of its key elements for application to the design of loaded structural members
- new materials - like lithium niobate, the workhorse of the laser industry for harmonic generation and modulation; block co-polymers for biotechnology and electronics, fiber-polymer composites for aircraft; and spatially-varying materials as new lasers and IR focal plane arrays.

As a result of the success of the IDL's and the recognition of the importance of materials science and engineering, the number of universities with departments in materials has grown from 11 in 1964, to 29 in 1970 and 51 in 1985. Universities world-wide adopted names like Materials Science and Engineering for their departments, and industries and government labs created Materials Departments for conducting interdisciplinary research. Half of the basic research sponsored by the government in materials science is performed at these labs.

While the materials research results were highly important, the profound effect of the ARPA IDL program was that it was the first to recognize and fund interdisciplinary research. Its success and the value of cross-disciplinary research has set an example for other faculties and university administrations. Today's university register is incomplete without its list of interdisciplinary centers - in areas as diverse as information and technology, design, urban studies, robotics, optics, the environment, teaching, art, and history.

Thus, DARPA can take pride in creating Materials Science and Engineering, the field which Dr. George Keyworth II, a physicist and Scientific Advisor to President Reagan, said in 1983 "may be the most important field of science in the U.S. today."





## Explosive Forming

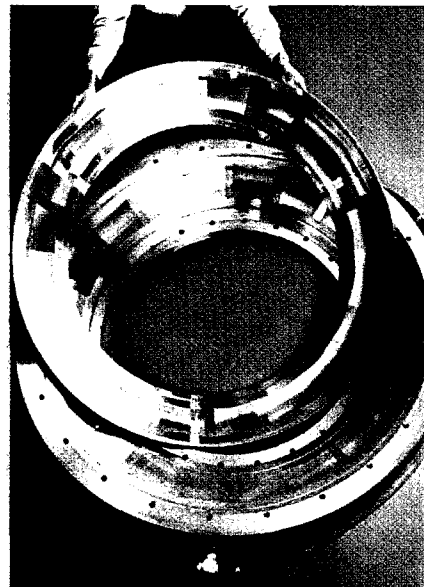
**Objectives:** To develop the technology of explosive metal-working as a part fabrication technique

**Contractor:** University of Denver

**Agent:** AF Materials Lab

**ARPA PM:** R. Thomson

**Time Period:** 1968-1972



Example of Explosively-Formed Part

### Key Factors in Program Success:

- Program had a very effective champion
- Denver set up a special institute to develop and transfer technology
- Formed a company to produce the products — Explosive Fabricators
- Adequate funding and time duration (\$3M; >4years)

### Application and Impact:

- Al, Ti, stainless steel, carbon steel, inconel
- Reproducibility of 0.5%
- SR-71 Afterburner Ring (P&W)
- Jet engine main bearing housing (P&W)
- Aircraft skin — P3 Orion (Lockheed)
- Jet engine diffusers (Rohr)
- All Navy warships in past 17 years use this process to weld super-structures to the deck

## **PROGRAMS RESULTING IN TECHNOLOGIES BEING USED IN DoD's OR OTHER AGENCY'S SYSTEMS**

### **EXPLOSIVE FORMING**

In the mid-60's ARPA decided to support an effort proposed by the University of Denver to use explosives for metal part fabrication. In essence, a female mold (die) was made for the part. The metal plate was placed over it with the space between the plate and the mold being evacuated. The plate plus die are then immersed in a water tank in which an explosive charge is set off. The water serves as the coupling agent for the shock which forces the metal plate against the die. The reproducibility of this process is remarkably high - 0.5 percent - and has been used to successfully manufacture a variety of large metal structures or parts..

The range of the DoD products which Explosive Fabricators, Inc. has made is extensive: jet engine diffusers for Rohr; Titan "manhole" covers for Martin/Denver; SR71 afterburner ring for Pratt & Whitney; rocket engine seals for Rockwell International; P3 Orion aircraft skin for Lockheed Aeronautics; tactical missile domes for Lockheed Missile and Space Company; jet engine sound suppressors for Hexcel; APU heat shields for Garrett Turbine Engine, and many others. A number of factors contributed to the success of the program. Most important, it had an effective champion - a bright pleasant person at the University of Denver who was persistent and knew how to get things done. Also, the University of Denver formed a separate institute to carry out this program, thus the key people could avoid getting mired down in university politics. Further, a separate company was formed - Explosive Fabricators, Inc. - to produce these products.



## Beryllium Mirrors

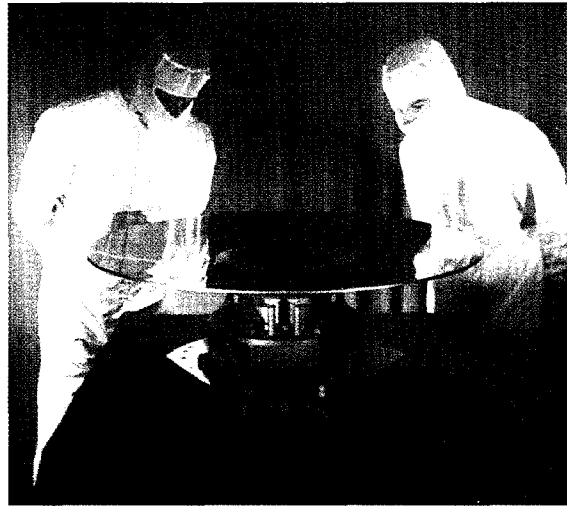
**Objectives:** To develop the technology to make large, precise, low weight and low scatter, stable beryllium mirrors

**Contractor:** Perkin Elmer

**Agent:** Army Missile Command

**ARPA PM:** R. Thomson

**Time Period:** 1968-1972



NASA/JPL's IR Telescope Technology:  
Testbed Primary Mirror Assembly

### Key Factors in Program Success:

- Provided sufficient funding to do the job (\$1.4M)
- Used an agent who would be a user of the technology
- Funded a vertically oriented company thus making it less difficult to get the results used

### Application and Impact:

- The all-beryllium cryogenic optics for NASA's IR Astronomical Satellite Program
- 15 inch aperture airborne, cryogenic, beryllium long wave IR telescope system for the Midcourse Airborne Target Signature Program for ABMDA
- Trident 11 Mark 6 guidance stable member

## **BERYLLIUM MIRRORS**

From FY68-72 ARPA funded a program with the Perkin Elmer Corporation to develop the technology for fabricating large, stable, low weight mirrors from beryllium, a very light-weight metal, for use in space applications. The early focus of the program was in developing and evaluating improved forms of beryllium. Perkin Elmer was successful in improving the thermal stability of beryllium surfaces 10-fold, and developing techniques (powder metallurgy, hot isostatic processing, pressureless sintering) for making it possible to fabricate large Be structures. Further ARPA funded efforts led to surface polishing techniques to reduce scattering in the IR by 2 to 8-fold, the successful development of thin film coatings techniques, and a demonstration of the long-term stability of Be surfaces.

DoD applications have included the all-Be, 15 inch aperture long wave IR telescope system for ABMDA's Midcourse Airborne Target Signature program; the fabrication of a lightweight, 40 inch, f/0.58, aspheric mirror for the AF; experimental near-net-shape production of the Trident 11 MK6 guidance stable member; and the 85 cm Be mirror assembly for NASA JPL's IR Telescope Technology Testbed for eventual use in NASA's Space Infrared Telescope Facility, to be launched early in the 21st century. From a management perspective, this program was successful because the contractor was vertically oriented thus not requiring technology transfer out of the company; the agent (the Army) was a user of the technology; and, finally, ARPA provided the funding needed over a long enough period of time to solve the problems with the technology.



## Rare Earth ( $\text{Sm}_2\text{Co}_{17}$ ) Permanent Magnets

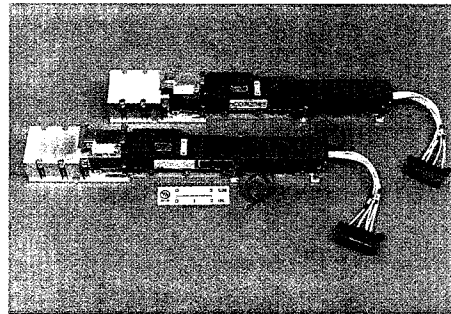
**Objectives:** Develop improved permanent magnets utilizing rare earths ( $\text{Sm}_2\text{Co}_{17}$ ) capable of high temperature operation

**Contractor:** U. of Dayton - Karl Strnat

**Agent:** AF Materials Lab

**ARPA PM:** R. Huggins

**Time Period:** 1969-1973



VTR-5114N5 TWT used on F-16

### Key Factors in Program Success:

- ARPA supported the best US scientist to do this research
- The PI organized conferences and invited industry
- The Japanese attended the conferences and were first to market
- US companies ignored results at first, but then followed Japanese



### Applications and Impact:

- High performance TWTs:
  - VTR-5114 N5 used in US AN/ALQ-135 EW system on F-15
  - QKW-2048 for Navy EHF Satcom Program
- Cryocoolers for IR sensors on Cobra helicopter and F-18

## RARE EARTH MAGNETS

From 1968 to 1972, ARPA funded a broad materials research program seeking high performance materials containing the rare earth series of elements. Among the funded efforts was one with Dr. Karl Strnat at the University of Dayton to develop the "second generation" of rare earth permanent magnets based on the  $\text{Sm}_2(\text{Co,Fe})_{17}$  intermetallic phases. Dr. Strnat was a leading US scientist in this area of research and he organized a series of conferences, inviting industry to attend, to stimulate interest in commercializing this technology. As has happened so often, US industry chose to ignore the implications of this work until forced by the Japanese competition to begin production of them.

The 2-17 magnet is now the preferred one for applications that demand a high energy product and coercive force combined with a low temperature coefficient and good magnetic property stability at temperatures up to 350°C. Their main application is in electro-mechanical and electronic systems for military and space applications. The newer Nd-Fe-B magnets have poorer temperature stability and cannot compete with the 2-17s in the military specialty markets. Principal applications have included high performance TWTs - Varian's VTR-5114N5 used in the US AN/ALQ-135 EW system on the F-15, and Raytheon's QKW-2048 for the Navy EHF Satcom Program - and in cryocoolers for IR sensors used, for example, on the Cobra helicopter and the F-18.



## Ceramic Turbine: Brittle Materials Design

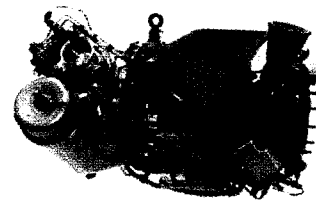
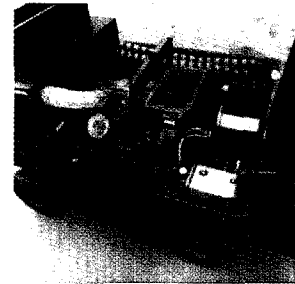
**Objectives:** Develop a total systems iterative approach to high temperature structural design with ceramics in highly stressed applications. Achieve 200 hours of auto engine rig operation at temperatures up to 2500°F. Encourage engineers to design with ceramics

**Contractor:** Ford/Westinghouse and later, Garrett AiResearch Corp.

**Agent:** Army Materials and Mechanics Research Center (AMMRC)

**ARPA PM:** M. Sinnott and E. van Reuth

**Time Period:** 1971-1978



99639-2

Ceramic Nozzles: APU Longevity

### Key Factors in Program Success:

- The world was ready for ceramics
- Adequate funding and duration of program
- Identified "show stoppers" early
- Champions were everywhere
- Leadership of the agent, N.R. Katz

### Application and Impact:

- Helped established a world-wide structural ceramics industry
- Army and Detroit Diesel testing modified 8V71-T engine in M109 Howitzer and M998 ammunition carrier at NATO
- Japan and US manufacture >\$100M per year of ceramic engine parts. Japan makes over 300,000 turbocharger rotors per year.

## **CERAMIC TURBINE: BRITTLE MATERIALS DESIGN**

In 1971, Dr. Maurice Sinnott, on leave at ARPA from the University of Michigan, decided to initiate a program to demonstrate and encourage the use of brittle materials in engineering design. The focus was to be on the development of ceramic components for gas turbine applications. A competitive procurement process resulted in a team of Ford and Westinghouse being selected - Ford to concentrate on auto-size engines and Westinghouse, ship-size engines. The program was to be a total systems iterative approach to high temperature structural design with ceramics in highly stressed applications. A goal at Ford of 200 hours of engine rig demonstration for representative duty cycle temperatures in a regenerated vehicular gas turbine was chosen, with uncooled ceramic components to operate at least 25 hours at 2500°F, considerably beyond the temperatures possible with uncooled metal components. The approach included major efforts in ceramic design, materials development, fabrication process development, and test and evaluation methodology.

By the end of the program in 1979, 200 hours of duty cycle durability on turbine test rigs (between 1930°F and 2500°F) were attained on reaction-bonded silicon nitride and silicon carbide used as combustors, stators, and turbine rotor tip shrouds. A 37 hour engine rig test was run with an uncooled ceramic rotor at temperatures up to 2500°F and speeds up to 50,000 RPM. Thus the Ford program demonstrated that design with brittle materials in highly stressed applications is possible and, in particular, that ceramics as major structural components in gas turbine engines are feasible.

This program started the "Ceramic Fever" that spread throughout the world in the late 1970s and early 1980s. The successful demonstration of ceramics in a gas turbine environment led to the establishment of ceramic programs in virtually every automotive or engine company in the world: GM, Chrysler, VW, Daimler-Benz, Toyota, Nissan, GE, Pratt and Whitney, and Rolls Royce. Important programs were established within DoE, NASA, and the Air Force to fund and monitor the progress of the ceramics efforts. Major programs were also initiated in Germany, Japan and Sweden to further ceramic development in these countries. The common thread throughout these programs has been the further development of materials, near-net shape fabrication processes, and techniques for designing with ceramics with demonstration objectives almost always being advancement in heat engine technology for either gas turbine, diesel, or spark ignition engines.

In recent years, DARPA has funded a ceramics insertion program which includes an effort by Detroit Diesel to extend the life of the 8V71-T engine which is used in the M109 Howitzer and the M998 ammunition carrier. Upon substitution of this modified engine for the current engine the horsepower is raised from 480 to 530HP with only a \$400 increase in parts cost. The engine is currently in the middle of a 400 hour NATO test and is doing very well. Further, at Allied Signal (formerly Garrett Corp.), DARPA funded the insertion of ceramic nozzles into the Series 85 Auxiliary Power Unit which is used in AF ground carts for the Lockheed C-130H with over 18,000 hours of successful testing.





## Glassy Carbon

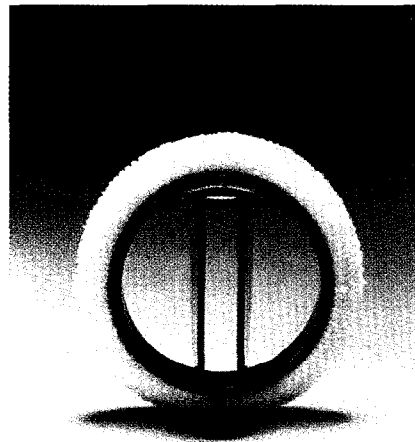
**Objectives:** Develop understanding of and techniques for producing "glassy" carbon, a form of pure carbon which is porous (low weight) and strong, and possesses the chemical inertness of pure carbon

**Contractor:** University of Michigan, Penn State, Gulf General Atomic, Battelle NW

**Agent:** Defense Supply System - Washington

**ARPA PM:** M. Sinnott, H. Test

**Time Period:** 1971-1974



Mechanical Heart Valve

### Key Factors in Program Success:

- Program PI was a champion and an entrepreneur
- Glassy carbon is a unique material which was bound to find unusual applications

### Application and Impact:

- In 1990 FDA approved glassy carbon for use as a heart valve
- St. Jude Medical Co. produces about 100,000 heart valves per year for \$200M; the taxes on this pays for the program annually by 40 fold
- A fraction of these are sold to VA Hospitals
- Small joints are now being developed

Commercially, Japanese and US automobile producers have introduced a variety of silicon nitride components into production engines. These include glo-plugs, a pre-combustion chamber, rocker-arm pads, turbocharger rotors, fuel injector links, cam roller-follower, fuel injector check balls, compression brake master cylinder wear face, and the exhaust gas control valve. All of these components are manufactured in Japan although some may undergo final machining and assembly elsewhere. By the end of 1990, the market for these was estimated to be \$100M. Currently it is estimated that over 300,000 silicon nitride turbocharger rotors are now manufactured annually. Their use is driven by performance and environmental quality issues. Thus, as a result of the ARPA program, ceramics have become engineering materials. This program succeeded because the timing was perfect for it; ARPA provided adequate funding over a sufficiently long period of time; the program was managed to identify "show stoppers" early; champions were everywhere; and the leadership and participation of the highly qualified staff at AMMRC, ARPA's agent for the program.

## GLASSY CARBON

From 1971 to 1974, ARPA supported research on "glassy" carbon at the University of Michigan, Penn State, Gulf General Atomic, and Battelle NW. This material was unique because it is a foam material composed of pure carbon which gave it low weight, high strength, and chemical inertness. Techniques were developed for producing it with an exceptionally high void volume (97%), high surface area combined with self-supporting rigidity, low resistance to fluid flow, and resistance to very high temperatures in a non-oxidizing environment. It has a bulk density of about 3 pounds per cubic foot.

While applications are being found in electro-chemistry, its most successful use has been as body implants, especially heart valves. Development of the valves started about three years after the end of the ARPA program with production commencing in 1985. In 1990, the FDA gave their approval for using these as implants. As a result of the ARPA program, all heart implant valves are made of glassy carbon with about 100,000 of them being sold per year with sales of about \$200M (the Federal taxes on which pay for the total program every year by more than 40 fold). Small joints are now being developed (fingers, toes), and human implants of these should begin in 1997. A fraction of the heart valves are sold to Veteran's Hospitals. The PI at Michigan was a champion for the technology and a university-based entrepreneur who marketed the technology to interested companies.



## High Performance Infrared Optics

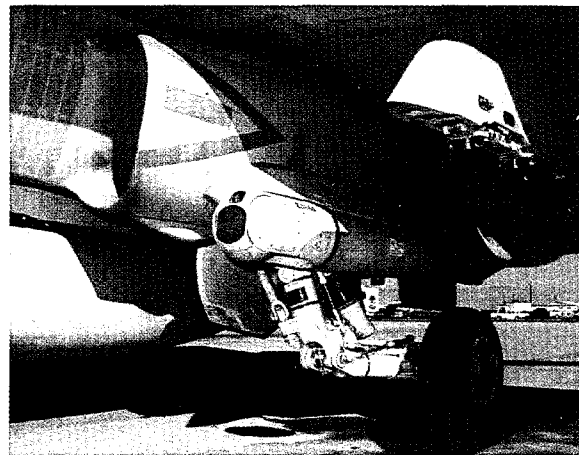
**Objectives:** Develop transparent materials, and surface preparation and coating techniques for window materials for near IR and long wave IR optics with low absorption and scatter

**Contractors:** Many

**Agents:** Many

**ARPA PM:** M. Stickley

**Time Period:** 1972-1978



F/A-18 FLIR on a F/A-18 Hornet Aircraft

### Key Factors in Program Success:

- Insisted on a spirit of openness and cooperation between contractors
- Invited suppliers to attend program review meetings even though they were not funded
- Evolution of a commercial market for these optics helped make them available to the DoD

### Applications and Impact:

- Low loss coatings for IR windows for PaveTack, LANTIRN, and F18 FLIR
- Vital to success of Libyan air strike in 1986 and Persian Gulf War in 1990
- First enabled the US to "own the night"
- US has 60% market share of the \$50M world-wide IR optics business

## HIGH PERFORMANCE IR OPTICS

In 1971, the Strategic Technology Office (STO) of ARPA sought help from the Materials Sciences Office to develop solid window materials for use with high energy lasers. A broad program involving many contractors was then initiated to develop the range of technologies needed for such a window: pure starting materials, fabrication techniques for making large windows, polishing techniques which would not leave residual surface absorption, ultra-low-loss coatings, and techniques to measure very low absorption losses. Materials which were explored included alkali halides and fluorides as well as zinc selenide and zinc sulfide.

While the technology for fabrication of large, low-loss, coated windows was successfully developed, few windows were actually utilized in large gas-dynamic CO<sub>2</sub> or HF lasers as these systems resorted to aerodynamic windows. The technology, however, got into the hands of the growing, specialty optics companies as a result of (1) attendance at contractor meetings where the techniques developed in the program were openly presented and discussed, and (2) the movement of people from the aerospace contractor organizations (e.g. Hughes Research Labs) to small optics companies. As a result, a \$50-100M annual optics components market has developed to supply the laser industry and the aerospace companies with high quality optics. The most significant DoD application of this technology has been as FLIR windows for the F-111 Pave Tack System and the F/A-18. Both of these systems were involved in and "absolutely vital to the success of the Libyan Air Strike in 1986" (quoted from a letter written by Ford Aerospace and Communications Corp.) and that "the impact was dramatic." The Pave Tack system is used by NATO forces in Europe and the Republic of Korea forces. The F/A-18 FLIR system is deployed on strike F/A-18 aircraft deployed around the world. The "system performance of these payloads would have been impossible without the use of these ZnS windows." Finally, such systems were used in the Persian Gulf War enabling night operations since successful night operations required being able to "see" in the IR and also to sense 1.06 micron YAG laser radiation reflected from the target. These advanced materials enabled the US to "own the night."



## Platinum Silicide IR Focal Plane Arrays

**Objectives:** Develop an IRFPA technology which would be of lower cost, more produceable, and have higher yield than HgCdTe

**Contractor:** Rome Lab - F. Shepherd;  
RCA Labs; Loral

**Agent:** Rome Lab at Hanscom AFB

**ARPA PMs:** M Stickley, S. Roosild

**Time Period:** 1973-1978



B-52 and its AAQ-23 Camera



### Key Factors in Program Success:

- The effectiveness of a champion - Freeman Shepherd - who invented it and pushed its development for 20 years
- AF R&D management which supported Shepherd's efforts for 20 years

### Applications and Impact:

- B-52 IR Camera (AAQ-23)
- Cost of \$200K and MTBF of 5000 hours
- Replace HgCdTe cameras in AF inventory which cost \$700K with a MTBF of 350 hours
- Greater than \$10M savings per year to AF B-52 wings

## PLATINUM SILICIDE FOCAL PLANE ARRAYS

In the very early 70's, Dr. Freeman Shepherd invented and reduced to practice at the Air Force Cambridge Research Labs (now AF Rome Lab) a new, near-IR sensor based on silicon technology. Given the high cost and poor reproducibility of the competing HgCdTe technology, ARPA elected to develop the PtSi sensor technology starting in 1973. As a result of the ARPA program and continuing efforts by the Air Force over the succeeding 10 years, this technology is now being produced by Loral for installation as an IR camera (AAQ-23) in the Air Force's B-52 fleet. The pre-production version of this camera was used in October 1994 by the AF's Air Combat Command in the lead B-52 to validate bomb run coordinates as Iraqi forces advanced towards Kuwait.

The success of this technology has been due virtually entirely to the efforts of its champion, Freeman Shepherd, over these 20 or more years. He has been and continues to be involved in all stages of its evolution. It required a constant, vigilant effort on his part to keep the technology alive. The important feature of PtSi IR camera is its 5000 hour MBTF (compared to 350 hours at best for HgCdTe for those in the AF inventory), and its lower cost (\$200,000 compared to \$700,000 for HgCdTe). The AF estimates this camera will save them more than \$10M per year in reduced maintenance costs. Other advantages of the technology include uniformity of response from pixel-to-pixel, high manufacturing yield, low cost, and freedom from image "ballooning" when over-illuminated. US manufacturers of PtSi technology include Loral, Kodak, and David Sarnoff Labs. Foreign manufacturers include AEG (German) and Mitsubishi; Mitsubishi was the first market with a commercial system. Other US companies purchase focal planes and sell cameras for security systems, and for thermal inspection in manufacturing operations.



**Advancement of Reliability, Processing & Automation of Integrated Circuits  
“ARPA/IC/NBS”**

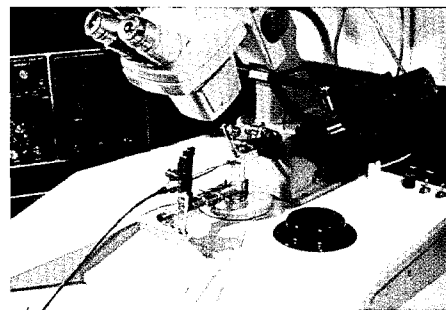
**Objectives:** Achieve affordable reliability in complex electronic systems through improved measurement technology to control and specify: incoming materials, manufacturing processes, and completed devices.

**Contractor:** Primarily NIST (NBS) in-house

**Agent:** None

**ARPA PMs:** M. Stickley, R. Reynolds

**Time Period:** 1973-1979



Linewidth Measurement Standard and Wire Bonding Techniques and Testing



**Key Factors in Program Success:**

- The attitude of the NBS staff: industry-problem-driven; comprehensive and thorough work; genuine cooperation with industry (not the usual ‘hand-off’)
- Completely adequate funding
- Program funded long enough to spin off results and have an impact

**Application and Impact:**

- Wire bonds and bond pull tests, test patterns, linewidth measurement, spreading resistance profiling, CMOS, SOS, ion-dose measurements, etc.
- Results permeate the infrastructure of the semiconductor electronics industry and system houses. For example:
  - at Martin Marietta Aerospace, solved serious reliability problem; saved ~ \$1M in costs on DoD missile program
  - 50 organizations were trained in linewidth measurement techniques

## **ADVANCEMENT OF RELIABILITY, PROCESSING AND AUTOMATION OF INTEGRATED CIRCUITS**

In the early '70s, the DoD's long standing problem of obtaining specialized integrated circuits (ICs) which would meet its reliability requirements at reasonable cost became serious. It seemed clear that the procurement of reliable ICs through "testing in" reliability had to be replaced by "building in" reliability. Thus a six year program was initiated with NBS for development of the measurement technology necessary to enable device manufacturers to exert more effective control over the materials and processes they use to make integrated circuits. Industrial contractors were also used through subcontract to NBS.

Work was carried out in 12 technical areas: resistivity and dopant characterization; crystal defects and contaminants; oxides and other insulator films; physical analysis techniques; film and layer thickness; materials for infrared detector arrays; materials and procedures for wafer processing; photolithography; microelectronic test patterns; wafer inspection and test; die and interconnection bonding; and hermeticity. Advances in measurement technology were made in each of the 60 measurement problem areas addressed during the course of the program. These advances were communicated to the industry through seminars and workshops, individual plant and agency visits, videotapes on selected measurement techniques, and publications, both in trade and archival journals and in a series of NBS reports on Semiconductor Measurement Technology specially established for this program. Over 220 reports of work conducted as part of this program have appeared in the technical literature.

Significant improvements occurred in performance and reliability of devices for DoD (and commercial) use; also, several DoD programs (e.g. the Trident) have saved millions of dollars through timely implementation of these measurement technologies. For example, the investigation of wire bonding of integrated circuits established new procedures now implemented in commercially available equipment which increased purchased circuit yields by as much as 35 times, and made possible large military hybrid circuits which utilize more than 500 wire bonds each. In programs which have employed this bonding test procedures, no field failure of devices due to faulty bonds has occurred. This program was successful largely because of the attitude of the NBS staff - they were industry-problem-driven; they did comprehensive and thorough work; and they genuinely cooperated with industry to transfer the technology.





## Gallium Arsenide Integrated Circuits

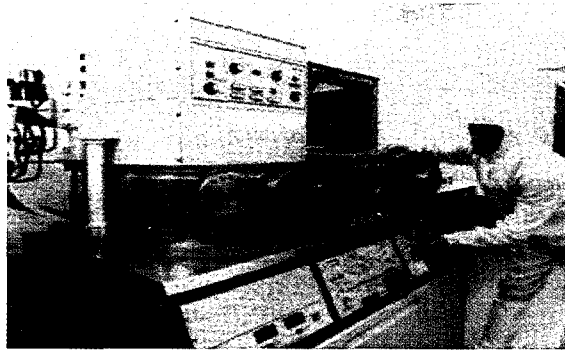
**Objectives:** To develop a GaAs IC technology offering higher speed, lower power, wider temperature range, and better radiation resistance than silicon ICs.

**Contractor:** Rockwell International and others

**Agent:** Rome Lab at Hanscom AFB and NCCOSC, San Diego

**ARPA PMs:** M. Stickley, S. Roosild, R. Reynolds

**Time Period:** 1974-1995



GaAs Facility with MBE Equipment

### Key Factors in Program Success:

- Strong military payoffs of the technology
- Continuity at ARPA and perseverance of the key program manager, S. Roosild
- Long term ARPA support (1974-1995)

### Application and Impact:

- Chips in the Precise Lightweight GPS receiver
- Pseudo-random code generator for NSA
- Accumulator and rate-reducer chips for smart terminals
- P3 ISAR Radar Processor
- Digital Signal Processor for OH-58D helicopter
- Motorola building a GaAs IC plant for IRIDIUM

## GALLIUM ARSENIDE INTEGRATED CIRCUITS

In 1974, ARPA initiated an effort with Rockwell International Science Center, Cal Tech and Stanford to determine the feasibility of making active gallium arsenide devices using ion implantation. The first effort led to the demonstration of ion-implanted gallium arsenide metal-semiconductor field-effect transistor logic gates. With this being successful, DARPA funded the first effort at Rockwell to make high speed, low power digital integrated circuits using Schottky barrier field-effect transistors. Digital GaAs devices were expected to have excellent potential for military systems because they should consume a fraction of the power, operate at much higher speeds, function over a wide temperature range, and be much more resistant to radiation than silicon components.

Despite the formidable materials and process challenges which existed, the effort was successful with the demonstration of fully functional, large-scale IC devices in 1980. In the 1981-1982 time period a GaAs IC pilot line program was initiated by DARPA to move the technology from the laboratory to manufacturing. As a result of these successes and because Rockwell decided to not attempt to commercialize the technology, GigaBit Logic, with funding from DARPA and with venture capital, was formed. Venture capital became available based on assurance of continued DARPA funding. This was necessary as commercial applications were still too far off, while military applications were still very attractive. In the late 80's DARPA initiated GaAs IC technology insertion programs with a number of DoD contractors. Some of the GaAs military applications are GPS receiver chips used in the Precise Lightweight GPS Receiver; a sine ROM accumulator and rate-reducer chip for smart terminals; and a pseudo-random code generator chip for NSA. D/A and A/D converter chips are currently under development. Meanwhile, commercially, Motorola is building a large GaAs plant to make ICs for IRIDIUM. This program was successful because of DARPA's staying power - both in terms of budget, and program manager continuity and perseverance. Most of all, the principal DARPA program manager, Sven Roosild, was a champion for the technology, and his continued presence at DARPA through the 80's was vital in keeping it alive. Hand-off to the Services for funding never seemed to be a possibility because the size of the funding needed would dwarf their other programs.



## Rapid Solidification Rate Processing

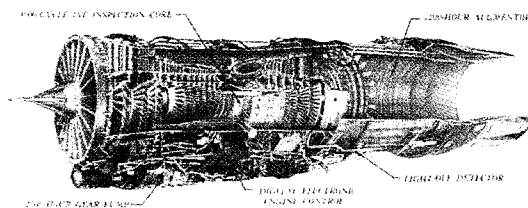
**Objectives:** Develop rapid solidification rate processing techniques ("powder metallurgy") for making high maximum temperature nickel-based superalloys for improved jet engine performance

**Contractor:** Pratt & Whitney

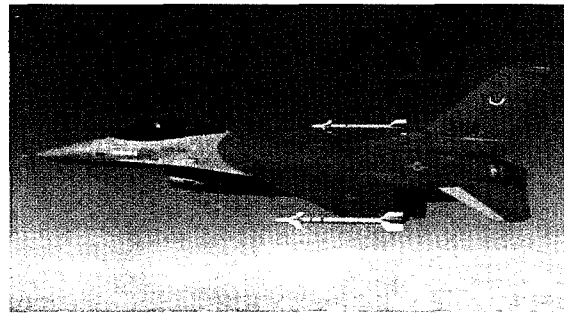
**Agent:** Air Force Materials Lab

**DARPA PM:** E. van Reuth, L. Jacobsen

**Time Period:** 1975-1986



F100-PW-220 Engine for F-16 Aircraft



### Key Factors in Program Success:

- P&W engine group listened to and utilized the results of the materials development group.
- R&D personnel were risk takers
- P&W had a real need to solve problem of failures and reduced performance

### Application and Impact:

- Compressor outer air seals in 4th and 5th shrouds, and 6th to 12th stators in F100-PW-220 engine resulting in extended engine life for the F-16
- GM built a RSR production facility to manufacture Nd-Fe-B magnets for lower cost dc motors

## **RAPID SOLIDIFICATION RATE PROCESSING**

In 1975, DARPA initiated a major effort with Pratt and Whitney to develop and apply 'rapid solidification rate' processing to the manufacture of aircraft turbine blades and seals which would exhibit higher temperature operation and higher wear resistance, respectively. Parts were formed in this process by starting with powdered material. The key step was to form the powder by rapidly quenching the molten metal. "Splat cooling" was the name given to the early version of this process by its inventor, Paul Duwez, of Cal Tech and DARPA's Materials Research Council. Rapid quenching made possible the freezing of mixtures of metals which would otherwise separate if cooled slowly (i.e. non-equilibrium mixtures). More importantly, this rapid cooling process helped to greatly assure the homogenization of impurities, which under normal (slow) cooling conditions would agglomerate and become a source point for future crack initiation or premature wear.

This program resulted in Pratt and Whitney successfully using these materials in the compressor outer air seals in the 4th and 5th shrouds and 6th and 12th stators in the F100-PW-220 for the F-15 and F-16 aircraft, and the 1st and 2nd stage compressors for the LAVI. Factors which bore on the success of this program were: it was funded at a vertically oriented company in which the material's users communicated with and used the results of the material's developers; Pratt and Whitney had a real need to find a solution to their turbine failure problem and reduced lifetime and performance; and the Pratt and Whitney personnel were risk-takers. As a final point, in the commercial arena, General Motors picked up this rapid solidification rate technology to manufacture Nd-Fe-B magnets for lower cost dc motors for their vehicles.



## Computer Aids for VLSI Modeling

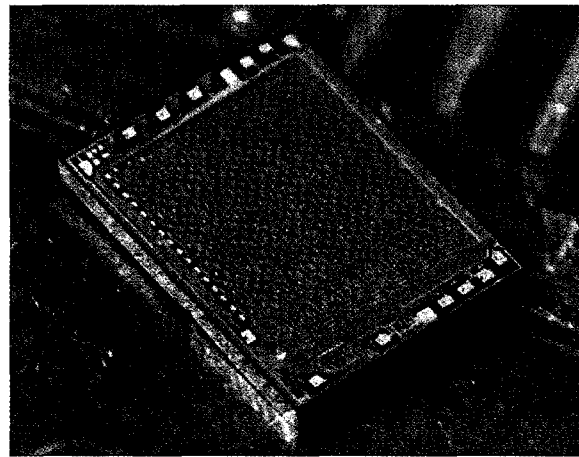
**Objectives:** Develop knowledge of semiconductor processing so as to enable design of integrated circuits having a high manufacturing yield through transfer to industry of computer design aids

**Contractor:** Stanford University

**Agent:** DSS-W for 7 years and the Army Electronics Lab for 9 years

**ARPA PMs:** M. Stickley, S. Roosild, R. Reynolds, J. Alexander

**Time Period:** 1975-1993



Integrated Circuit on a Penny

### Key Factors in Program Success:

- Wide programmatic latitude given to contractor
- Culture of Stanford to spin off technology information; Stanford established a center (the Center for Integrated Systems) to do this
- Completely adequate funding
- Long term funding by ARPA

### Application and Impact:

- Si and GaAs ICs of all sorts
- SUPREM codes licensed to more than 32 companies — Cypress, Eaton Corp., Harris, Honeywell, Hughes, Intersil, McDonnell Douglas, Motorola, TRW, Rockwell, TI, Xerox, Zymos, etc.
- ICs used in Trident missile and many other defense systems

## COMPUTER AIDS FOR VLSI MODELING

In the mid-70's it became clear to DARPA that in order to maintain high manufacturing yield of integrated circuits as the IC's became increasingly smaller, it would be necessary to improve the models, based on device equations and direct experimental results, of the various IC processing steps. Two efforts were initiated, one at the University of Florida and one at Stanford.

The Stanford program did extremely well. The silicon SUPREM computer programs have found widespread use, with the total distribution of SUPREM II, III, and IV to over 300 sites. In industrial firms and university research groups, SUPREM is generally regarded as the preeminent tool of its type. In many respects a "SUPREM simulation" has become a generic term. As industry interest grew in Stanford's results, Stanford formed a center - the Center for Integrated Systems - to help transfer the results to industry and to help manage the industry participation. Typically the CIS membership consisted of 20 companies, each contributing \$0.75M for membership and each being allowed to have one person on site at CIS to learn and to bring a real-world perspective. While the first 10 years of the effort concentrated only on silicon, GaAs process modeling was added in the mid 80's.

Virtually all companies who manufacture ICs for DoD use have licensed the process modeling codes from Stanford. Some of these companies are Harris Semiconductor, Honeywell, McDonnell Douglas, Motorola, National Semiconductor, Hughes Aircraft Co., NCR, RCA, Rockwell International, TRW, Texas Instruments, and others. DoD systems which use ICs designed using SUPREM include MILSTAR, NSA cryptoboxes, bus interface parts for DoD radios, radiation-hard ICs in the Trident missile, and many others. This program was successful because of the wide latitude given Stanford in what they pursued; the culture at Stanford to spin-off technology; and the significant funding level (typically \$700K-\$1M per year) and the long time duration of the program (more than 15 years) which enabled many improvements and refinements to be made to the codes thus greatly increasing their utility to industry.



## **Metal Matrix Composites for the Hubble Space Telescope**

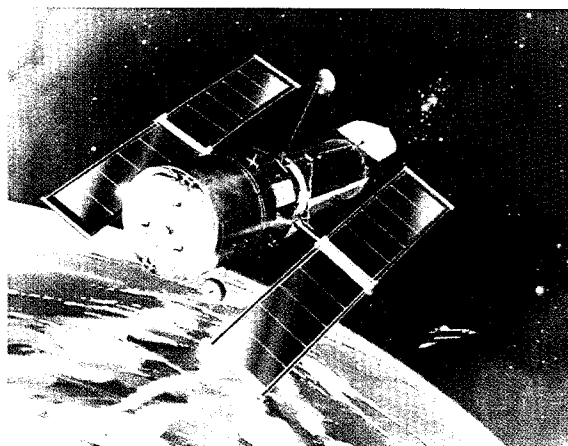
**Objectives:** To demonstrate that special metal matrix composites could solve problems of thermal distortion of satellite-borne antennas caused by non-uniform solar illumination

**Contractor:** Lockheed Missile and Space Co., Inc.; DWA Composite Specialities; and Material Concepts, Inc.

**Agent:** Air Force Materials Lab

**DARPA PM:** E. van Reuth

**Time Period:** 1978-1981



Hubble Space Telescope with Graphite/  
Aluminum Metal Matrix Composite Antenna  
Boom and Wave Guide

### **Key Factors in Program Success:**

- Tech transfer occurs more easily by technology insertion
- LMSC is a prime aerospace contractor who could coordinate and manage the program across many management levels (e.g. NASA to the subcontractors)

### **Application and Impact:**

- The mast is operating on the Hubble thus avoiding a >300 fold signal reduction if the original design had been used
- A weight reduction of 60% (35 lb.) was achieved vs. graphite/epoxy along with increased stiffness and reduced thermal distortion

## **METAL MATRIX COMPOSITES FOR THE HUBBLE SPACE TELESCOPE**

In FY78, DARPA initiated a program with Lockheed Missiles and Space Company, Inc. to design, fabricate, and deliver to NASA a prototype antenna mast for use on the Hubble Space Telescope. Nonuniform solar heating of a conventionally-fabricated antenna mast was expected to lead to a severe degradation in performance of the antenna. Thus the objective was to design a mast which would have nearly zero thermal expansion/distortion. This was to be achieved by balancing the positive thermal expansion of aluminum with the negative coefficient of expansion of the reinforcing graphite fibers. The design requirements were light weight, stiffness, and dimensional stability. Because this metal matrix composite was an electrical conductor, the mast was fabricated into a waveguide which served as the feed for the electrical signal to the antenna.

In the delivered prototype, the weight was reduced by 60% vs. the design using a graphite/epoxy mast with a separate aluminum waveguide; the stiffness was increased; and the near-zero thermal expansion of Gr/Al coupled with good thermal conductivity resulted in achieving acceptably small thermal-structural deformations of the antenna. This antenna is now functioning on the Hubble Space Telescope. Compared to conventional technology development programs, this program was successful because of its retrofit (or technology insertion) nature, and because the funding was through a prime contractor who had the right connection into the ultimate customer, NASA, and who successfully coordinated the activities of the subcontractors.





## Lightweight Al-Li Alloys

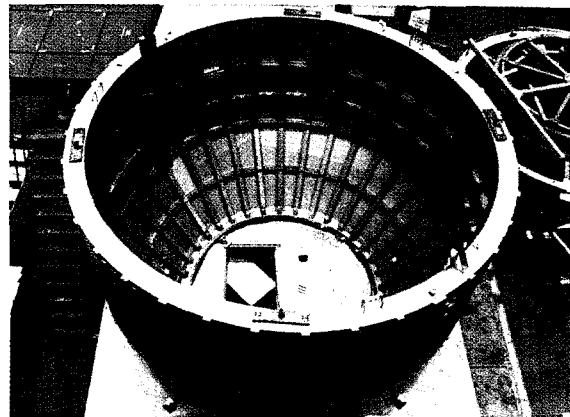
**Objectives:** Develop the technology for welding of aluminum-lithium alloys for use in construction of large payloads to be launched into space

**Contractor:** Lockheed Space Systems Division

**Agent:** AF Materials Lab

**DARPA PMs:** E. van Reuth,  
L. Jacobsen

**Time Period:** 1978-1982



Titan Missile Payload Adapter

### Key Factors in Program Success:

- Contractor was a large aerospace prime which had a direct connection to the application
- Contractor had a strong metallurgical capability at their research lab which they used

### Application and Impact:

- The Titan missile payload adapter which was 14 feet in diameter and 17 feet high
- 350 pounds of launch weight was saved yielding a cost saving of \$8M
- Various sensitive applications

## **LIGHTWEIGHT Al-Li ALLOYS**

In the late 70's, DARPA initiated a program with Lockheed Space Systems Division to develop the technology of welding aluminum-lithium alloys having the promise of reduced density and increased stiffness. At issue was understanding how to prepare these materials for welding including impurity control in the base Al-Li materials and in the welding agents.

Within 18 months, the metallurgists at Lockheed had developed the welding techniques for the 80/90 Al/Li alloy and applied it to the construction of space hardware. One of the most impressive structures made from this material was the Titan missile payload adapter, which was 14 feet in diameter and 17 feet high and fabricated from 3" thick plate. By using this alloy, a 10% weight saving was achieved. At current launch costs of \$50,000 per kilogram, this equates to a cost savings of over \$8M. Other DoD uses were made of these materials but their uses are sensitive. This program had a DARPA investment of \$2M and a Lockheed investment of \$10M and resulted in the production of 400,000 lb. per year of Al-Li alloys for four years. This program was successful because it funded a prime contractor having a direct connection to the applications and an excellent metallurgical capability at their research facility.



## Precision, High Performance Ceramic Bearings

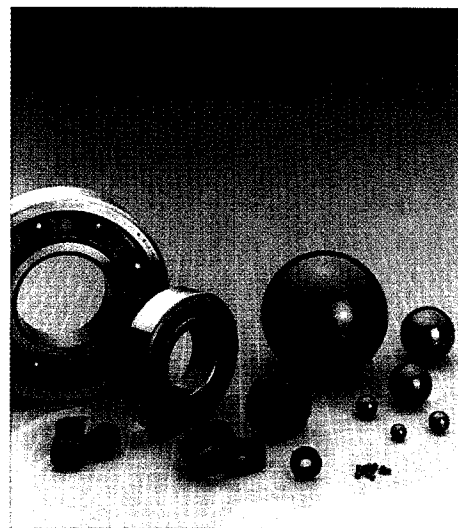
**Objectives:** Develop the technology to make ceramic bearings and apply them to DoD systems, including spin and gimbel bearings for IR seekers for missiles, gyros, air-cycle machines, auxiliary power units, and other applications

**Contractor:** Hughes Aircraft, Raytheon, Allied Signal, General Dynamics, Pratt and Whitney, TA & T

**Agent:** Various

**DARPA PM:** M. Buckley, S. Wax, W. Coblenz

**Time Period:** 1978-1989



Si<sub>3</sub>N<sub>4</sub> Ceramic Bearings

### Key Factors in Program Success:

- The technology was inserted into current systems; new systems did not have to be developed
- Ceramic bearings have major advantages over steel bearings: shock resistance, fatigue life, wear life, less friction

### Application and Impact:

- Gyros for F-18, AV-8, F-16 and various helicopters
- IR seeker bearing for the Navy Standard Missile and AF Sparrow Missile
- Solved steel bearing failure problem in IR seeker upon landing on aircraft carrier
- Greatly extended life and better performance

## **PRECISION, HIGH PERFORMANCE CERAMIC BEARING TECHNOLOGY**

To achieve a stronger focus on potential DoD applications of ceramics other efforts beyond ceramic engines were initiated by DARPA. One of the most successful of these has been the development of solid lubrication ceramic bearings. At Hughes Aircraft, titanium carbide ceramic coated metal ball bearing technology has resulted in enhanced manufacturing yields of the bearings, better performance, and longer life gyroscopes for several applications including standard navigation-guidance systems for F-18, AV-8, and F-16 production aircraft and for several types of helicopters. Production is pending of navigation-guidance systems for strapdown applications such as the MARK 48 Torpedo and the ASW SEA LANCE programs.

Further, Raytheon has developed all ceramic (silicon nitride) bearings for IR seekers for the Navy's Missile Homing Improvement Program at China Lake. Spin and gimbal bearings in IR seekers for Navy Standard Missile II Block 3B and Sparrow (AIM-7R) upgrades have a projected 800% life increase over steel bearings; flight tests are underway. Steel bearings in this application were found to not be able to take the impact of landing on a carrier, and their use was correlated with failure of the missile to hit the target. On the other hand, silicon nitride bearings have been found to have higher impact resistance, and their repeated tests in this application led to no failures, a dramatic difference relative to steel. Other benefits of silicon nitride bearings relative to steel are up to 10 x greater wear life, 3 to 50 x greater fatigue life, 50% greater speed, a 1000°F temperature capability, a 10-20°F reduction in heat generation, corrosion-resistance, nonmagnetic and electrically insulating, and freedom from need for lubrication. Allied Signal has also used ceramic bearings in air-circulating machines in aircraft. Currently 10 are under test in F-15s, and four in C-130s. A commercial market of about \$9M/year exists for such bearings.

Finally, NASA's Space Shuttle Discovery launched July 13, 1995, used a silicon nitride hybrid bearing in the main engine high pressure oxygen pump. Their goal is to achieve tens of missions between overhauls. Steel bearings had unacceptable wear necessitating too-frequent replacement. The silicon nitride bearings after 10,000 seconds (5 mission lifetimes) show no bearing or race wear upon disassembly and inspection. The last three shuttle flights have used ceramic-hybrid bearings.



## Retirement for Cause

**Objectives:** To develop the technology and procedures for retiring rotating components in aircraft gas turbines based on when a quantifiable defect necessitates removal rather than when a certain time period or hours of service have passed.

**Contractor:** Pratt & Whitney

**Agent:** AF Materials Lab, Wally Reimann

**DARPA PM:** M. Buckley, S. Wax

**Time Period:** 1979-1986



Many of These Disks Retired from Service Have  
Useable Life Remaining

### Key Factors in Program Success:

- The efforts of W. Reimann, the program champion, to lead a highly coordinated government and industry program
- The realization that the payoff was very large
- DARPA and Air Force funding for seven years

### Application and Impact:

- RFC was applied to the AF F-100-PW-100/200 engine
- Over the period of 1986-2005, a savings of \$966M will accrue in engine parts costs
- An additional \$300M will accrue in labor and maintenance
- RFC is applicable to all gas turbines

## RETIREMENT FOR CAUSE

In 1979, DARPA initiated a program, jointly funded with the AF Materials Lab, to quantify the savings which might accrue to the AF if a different approach - retirement for cause (RFC) - were used to decide when to retire a rotating disc from a gas turbine engine. Total fatigue life of a component consists of a crack initiation phase and a crack propagation phase. Engine rotor component life limits, usually expressed as operating cycles or life limits, are analytically determined using lower bound, 1-occurrence-in-1000, low cycle fatigue characteristics. By definition 99.9% of the disks were being retired prematurely. Retirement for cause allows each component to be used to the full extent of its safe total fatigue life, retirement occurring when a quantifiable defect necessitates removal of the component from service. The defect size at which the component is no longer considered safe is determined through fracture mechanics analysis of the disk material coupled with the disk fracture critical locations, the service cycle, and the overhaul/inspection period.

Since the cost savings look enormous if this approach were to be used, a seven year program was initiated with the goal of implementing this system for the USAF F100 engine at the USAF Air Logistic Command's San Antonio Air Logistics Center. This has been achieved, with a total of 23 fan, compressor, and low pressure turbine rotor parts being managed under this philosophy.

As a direct result, life cycle cost savings of \$966M are projected for the AF F100-PW-100/200 engine systems over the period of 1986 to 2005. An additional \$300M in savings will accrue from labor and maintenance fuel savings due to the extension of the maintenance interval for the upgraded F100 core engine. The technology and procedures developed under this program are generic and can be used on any gas turbine engine. This program was successful because of the high level of coordination and team work maintained between the government and contractor personnel. This was largely due to the energies which the 'champion,' Wally Reimann of AFML, devoted to the program.



## SiC Particulate-Reinforced Aluminum

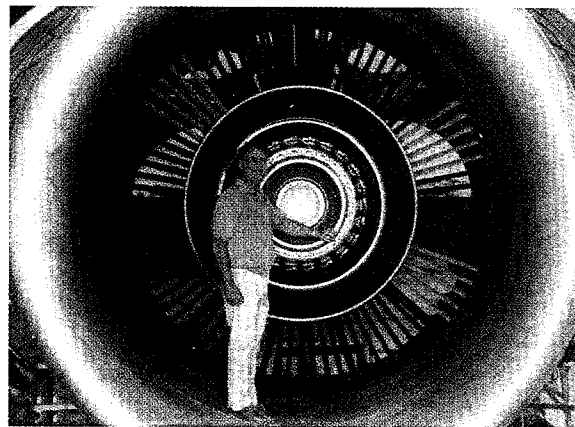
**Objectives:** Develop a low cost aluminum matrix composite with properties between standard structural alloys and carbon fiber-reinforced aluminum

**Contractor:** DWA

**Agent:** Naval Sea Systems Command

**DARPA PM:** L. Jacobsen, S. Fishman, P. Parrish

**Time Period:** 1981-1983



P&W 4090: guide vanes for 777 engine

### Key Factors in Program Success:

- Developed a data base for design trade studies.
- Services participated in follow-on research and development
- Defense Production Act, Title III, support for scale-up which made materials available

### Application and Impact:

- Fan exit guide vanes for large turbofan engines
  - Increased durability
  - Reduced cost (~ 1/2 X), replaced PMCs
- F-16 Ventral fins (replaces Al alloy)
  - Increased durability
  - 7X increase in lifetime
- Inertial Guidance Components
  - Low cost replacement for beryllium

## **SiC PARTICULATE-REINFORCED ALUMINUM**

Based in part on its successful experience with the carbon fiber-reinforced aluminum for the high gain antenna boom for the Hubble Space Telescope, DARPA became interested in lower cost forms of aluminum matrix composite materials that might have broader application to defense systems. Over the 1981 to 1983 time frame, DARPA funded an effort at DWA to produce and characterize lower cost particulate-reinforced composite aluminum materials. That effort produced a material property data base that formed the foundation for design trade studies that helped promote interest in these materials by the military Services.

All three Services, BMDO, and DNA have had programs to evaluate particulate-reinforced material over the last 15 years. Over the years, Service-funded development efforts have led to applications such as inertial guidance system components (a replacement for beryllium) and support structures (electronic racks) in weight-critical military applications. Enough military applications were generated to establish a Title III Defense Production Act Program to develop an industrial base and market to support the production of discontinuously-reinforced aluminum composite materials.

Material from that Title III program is now being utilized in two new applications. The ventral fins on the F-16 have been failing prematurely. The higher elastic modulus achievable with particulate-reinforced aluminum has been shown to substantially increase the lifetime of these components. Particulate-reinforced aluminum is being used in ventral fin replacements as the F-16s come in for rework. Particulate-reinforced aluminum is also transitioning into use to increase the durability and reduce the cost of fan exit guide vanes on the Pratt & Whitney PW4090 commercial engines. The materials will very likely be used in this same application on future generations of military turbofan engines.





## Ceramic Composite Armor

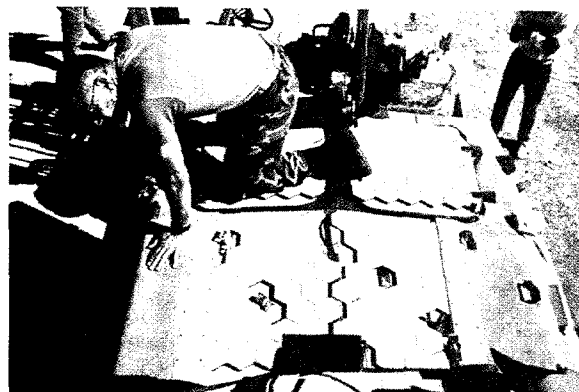
**Objectives:** Develop ceramic composite armor with multiple hit survival capability. Develop attachment system for applying to air and land vehicles.

**Contractor:** Lanxide Armor Products, Foster Miller, Los Alamos National Laboratory

**Agent:** Office of Naval Research,  
U.S. Marine Corp

**DARPA PM:** S. Wax, K. Adams, W. Coblenz

**Time Period:** 1984-1989



Tiles being installed on a LAV25

### Key Factors in Program Success:

- Discovery of novel processing technology for making ceramic composites
- Engineering a Velcro-like hoop and loop attachment scheme
- Desperate need for crew protection in aircraft against small arms fire and shell fragments
- Sustained support by two DARPA offices: Defense Sciences and Tactical Technology

### Application and Impact:

- Lightweight, ceramic-composites crew protection armor
  - Installed in C-141 aircraft flying in Bosnia saving 1000 lbs, compared with steel armor
  - Planned installation in C-130 aircraft for crew protection
  - Planned installation as top applique armor on U.S. Marine Corp Light Armored Vehicles
- Commercial application for wear parts in the mining industry.

## CERAMIC COMPOSITE ARMOR

Lanxide Corp. developed and patented a process for producing relatively low cost ceramic composites. The process, called DIMOX™, begins with a preform, which is placed against molten metal in a heated, oxidizing atmosphere. The metal converts to a ceramic via oxidation, and this matrix ceramic grows through the preform, infiltrating the filler without displacing it. The end product is a near-net-shape reinforced ceramic composite component. Some of these composites have excellent ballistic properties, including survival of multiple hits.

Lanxide joined with Foster Miller to develop an applique armor system (called LAST armor), which involves a hoop and loop attachment technology similar to Velcro. These two companies, working with Los Alamos National Laboratory, fielded a ceramic-based armor of particulate silicon carbide-reinforced aluminum oxide, which is bonded to Kevlar, creating a "composite-composite." The multilayer sheets (modules) can be attached quickly to a structure by fixing them to Velcro sheets previously glued to the structure.

These modular armor kits have been installed in cockpits of C-141 airplanes that fly into Bosnia. The armor protects the crew from small arms fire. Replacing steel armor with the lighter weight composite armor reduces the C-141 weight by about 1,000 pounds. The Air Force plans a similar installation for C-130's, and the Marine Corp is testing the applique ceramic composite tiles for top protection of Light Armored Vehicles.



## Insitu Metal Matrix Composite

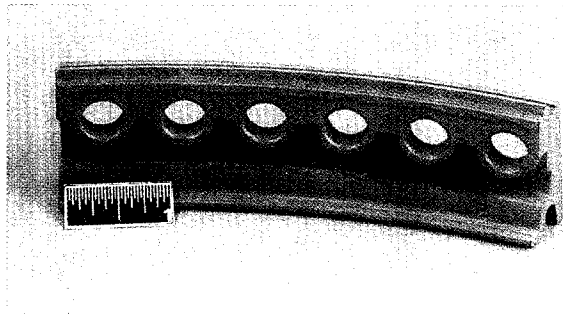
**Objectives:** Exploit invention by Martin Marietta of Exothermic Dispersion (XD™) technology for making metal matrix composites, especially particle-reinforced TiAl, for improved performance of propulsion systems.

**Contractor:** Martin Marietta Laboratories

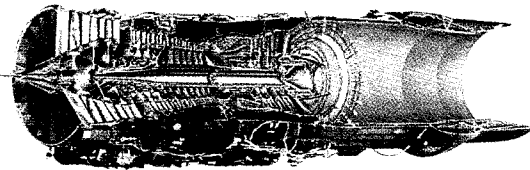
**Agent:** Naval Research Lab

**DARPA PM:** P. Parrish, W. Barker

**Time Period:** 1985-1989



Compressor Inner Shroud, P&W F119 Engine



### Key Factors in Program Success:

- Invention of novel technology to produce reinforced alloys using low cost processing.
- Materials are castable, forgable and weldable.
- Excellent agent, NRL, (R. Crowe) who successfully transitioned DARPA program to Navy Man-Tech follow-on, administered by Naval Air Development Center.

### Application and Impact:

- Compressor inner shroud for the P&W F119, and for the F-22 ATF
- Potential for:
  - Fins on SLAT missile
  - Turbocharger wheels and diesel engine valves for armored vehicle applications
- Reinforcement of TiAl doubles strength of monolithic alloy

## INSITU METAL MATRIX COMPOSITES

In 1984, researchers at Martin Marietta Laboratories invented a method of producing metal matrix composites which results in materials having excellent mechanical properties and which are readily processed by casting, forging, and rolling, or by consolidation of powders produced by rapid solidification processing. The technique, Exothermic Dispersion (XD<sup>TM</sup>), involves producing refractory reinforcing particles or whiskers insitu in molten alloys by a chemical reaction. Under DARPA support from 1985-89, MML developed titanium aluminide (TiAl) matrix alloys reinforced with titanium diboride particles (0.8 vol. % TiB<sub>2</sub>). The Ti-Al alloys are lightweight, but in the unreinforced condition have only modest high temperature strength which precludes their use in many aerospace applications. Reinforcing by the XD process approximately doubles the strength and greatly prolongs the creep rupture life at 800C, a typical application temperature. These alloys can be welded without destroying the reinforcing phases.

The effort was transitioned from DARPA to a 3-year Navy Man Tech program with the goals of demonstrating two different applications: replacing stainless steel in the FA/18 gunblast diffuser which would save 35 pounds; and installation as fins on the SLAT missile to enable withstanding substantial aerodynamic loading as well as high temperatures.

Production of XD TiAl flight hardware will begin in 1996 for Pratt & Whitney's F119 engine which is to be installed in the F-22 Advanced Tactical Fighter. The first component will be a compressor inner shroud. Other emerging turbine engine production applications are being developed at Rolls Royce. Potential applications of XD alloys for non-turbine military uses include missile fins, turbochargers, and diesel engine valves for armored vehicle applications.



## High Temperature Superconductors

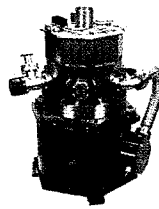
**Objectives:** To develop the new high temperature superconducting materials ( $\text{YBa}_2\text{Cu}_3\text{O}_7$ ) into practical materials, and to demonstrate their performance in military systems

**Contractor:** Westinghouse, and many others

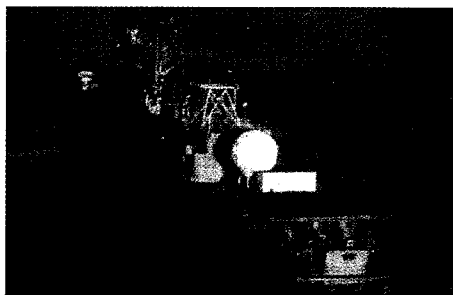
**Agent:** Naval Research Lab, ONR

**DARPA PM** K.Adams, F. Patten, S. Wolf

**Time Period:** 1987 - Present



Cryogenic Subsystem for AN/SPQ-9ADM Radar to be Installed on the XUSS- Decatur



### Key Factors in Program Success:

- DARPA's "staying power" in support of the program
- The intent at the outset to demonstrate the technology by insertion into weapon system(s)
- The personal commitment of the DARPA PM, F. Patten

### Application and Impact:

- The ultrahigh Q of the superconducting reference cavity will result in greatly reduced phase noise from a radar
- This enables the radar to have very high clutter rejection so as to be able to detect cruise missiles in clutter

## HIGH TEMPERATURE SUPERCONDUCTORS

In 1987, DARPA initiated a program to develop and apply ceramic superconductors having a useful operating temperature somewhat colder than liquid nitrogen (in contrast to earlier superconductors which operate within 10K or less of absolute zero). The beginning of this new program was announced in Constitution Hall in Washington, D.C. and attended by President Reagan, the Secretary of Defense, the Secretary of State, the President's Science Advisor, and other top-level government luminaries - clearly a remarkable beginning for a new government program. The program focused on the processing, fabrication, and demonstration of the use of these new materials. Bulk materials in the form of fibers, wires, and various shaped monoliths such as bearings were developed along with thin films on substrates for application to electronic systems and microelectronics. Many contractors were involved.

In the course of nine years the technology has progressed to a point where, in one project, an ultrahigh Q reference cavity will be tested in a SPQ-9B ADM ship defense radar. The result will be a high spectral purity, low off-frequency-phase noise, rf source which will enable the radar to have very high clutter rejection for detecting cruise missiles in clutter. This program was successful due to DARPA's "staying power" with the program, and the program philosophy of developing components which could be inserted into existing weapon systems.



## Appendix A.

### MAJOR THRUST AREAS

The following is a chronological listing from 1960-1987 of the major thrust areas and the approximate years these thrust areas were funded:

ARPA Interdisciplinary Labs	1960 - 1972
Crystal Growth	1962 - 1972
Conduction in Organic Crystals	1966 - 1969
Stress Corrosion Cracking	1966 - 1970
Coupling Program (Univ. plus Industry)	
· Carbon Filament Composites	1967 - 1971
· Polymer Composites	1967 - 1974
Armor I/Fracture	1967 - 1975
Explosive Forming	1968 - 1972
Beryllium Research	1968 - 1972
Laser Self-Damage	1968 - 1978
Mass Transport in Oxides	1968 - 1970
High Temperature Materials	1968 - 1970
NDT	1968 - 1971
Glass Materials	1968 - 1972
Solid State Lasers	1969 - 1977
Fine Powder Technology	1969 - 1972
Rare Earths	1969 - 1973
Materials Research Council, Def. Sci. Res. Council	1969 - Present
Diamond from Vapor Growth	1969 - 1972
Gallium Arsenide Research	1970 - 1973
Explosive Forming	1970 - 1972
Amorphous Semiconductors	1970 - 1973
Ceramic Turbine: Brittle Materials Design	1971 - 1980
Glassy Carbon	1971 - 1974
Small Particle Detection and Characterization	1972 - 1975
Laser Windows/Surfaces/Coatings	1972 - 1978
High Conductivity Polymers	1972 - 1990*
Superconducting Machinery	1972 - 1974

\* Transferred to the Electronic Sciences Division of the Defense Sciences Office when DARPA was restructured in 1981.



Homopolar Motors	1972 - 1977
Surface Science/Catalysts	1972 - 1976
Advanced Battery Chemistry/Technology	1972 - 1978
Fiber/Integrated Optics/Detectors/Sources	1972 - 1980*
Two Micron Photocathodes	1972 - 1978*
Superplasticity of Steel	1973 - 1979
IDL Phase-Down Projects	1973 - 1974
X-ray Lasers	1973 - 1977
Schottky Barrier Focal Plane Arrays	1973 - 1978*
Ferrous Die Casting	1973 - 1978
Advancement of Reliability, Processing and Automation of Integrated Circuits	1973 - 1979*
Gallium Arsenide IC's	1974 - 1995*
Wear/Tribology	1974 - 1979
Computer Aids for VLSI Modeling	1975 - 1993*
NDE	1975 - 1980
Rapid Solidification Rate Processing	1975 - 1986
HgCdTe Focal Plane Arrays	1975 - Present*
Pyroelectric Detectors	1977 - 1989*
Metal Matrix Composites for the Hubble Space Telescope	1978 - 1981
Lightweight Al-Li Alloys	1978 - 1982
Precision High Performance Ceramic Bearings	1978 - 1989
Retirement for Cause	1979 - 1986
Carbon-Carbon Engine	1980 - 1989
Sensor Protection	1980 - 1992
SiC Particulate-Reinforced Aluminum	1981 - 1983
Laser Hardening Materials for Missiles	1981 - 1985
Dynamic Synthesis/Consolidation	1982 - 1983
Armor II	1982 - 1987
Ceramics Fibers from Polymer Precursors	1983 - 1987
RAM/RAS	1984 - 1986
Net Shape IR Domes	1984 - 1985
Ceramic Composite Armor	1984 - 1989
Insitu Metal Matrix Composites	1985 - 1989
High Temperature Superconductors	1987 - Present

\* Transferred to the Electronic Sciences Division of the Defense Sciences Office when DARPA was restructured in 1981.

## Appendix B.

### ARPA MATERIALS SCIENCES PROGRAM MANAGERS

The following is a chronological summary of the names of the people who have been materials sciences program managers and the approximate years they were there.

Charles Yost*	1960 - 1964	Ron Kerber	1983 - 1984
Edward Salkovitz*	1965	Ben Wilcox*	1983 - 1996
Robb Thomson*	1965 - 1968	William Snowden	1983 - 1985
Herb Test	1968 - 1976	Phillip Parrish	1984 - 1989
Robert Huggins*	1968 - 1970	Gene Farnum	1985 - 1987
Conrad Trulson	1969 - 1971	Arati Prabhakar*	1986 - 1993
Maurice Sinnott*	1970 - 1972	Kay Adams	1987 - 1989
Martin Stickley*	1971 - 1976	Dave Squire	1988 - 1991
Edward van Reuth*	1972 - 1983	Jane Alexander	1989 - Present
Stanley Ruby	1973 - 1978	Lou Auslander	1989 - 1991
Richard Reynolds*	1974 - 1989	William Barker	1989 - 1995
Arden Bement*	1976 - 1979	Rich Loda	1990 - 1993
Harry Winsor	1976 - 1981	LN Durvasula	1990 - Present
Michael Buckley	1977 - 1980	Bill Coblenz	1990 - Present
Loren Jacobsen	1980 - 1984	Jim Crowley	1991 - 1994
Sven Roosild	1980 - 1995	Bob Crowe	1993 - Present
Raymond Gogolewski	1981 - 1982	Jon DeVault	1993 - 1995
Joseph Friebele (part time)	1981 - 1985	Stu Wolf	1993 - Present
Frank Patten	1982 - Present	Larry Dubois*	1994 - Present
Steve Wax	1982 - 1986	Anna Tsao	1994 - Present
Robert Green	1982 (six months)	Tom Moran	1995 - Present
Steven Fishman	1982 - 1983		

\*Office/Division Director